COMMUNICATION SATELLITES

A summary of prospects for this revolutionary means of transmitting telephone and television signals over the entire earth. It now seems likely that the first such system will be operating within five years

by John R. Pierce

The first transatlantic telegraph cable was opened in 1866; the first transatlantic radiotelephone circuit, in 1927—a span of six decades. Another two decades passed before the unreliable radiotelephone circuits were supplemented by a transatlantic telephone cable. It now seems possible that no more than a decade will pass between the opening of the submarine telephone cable in 1956 and the inauguration of commercial communications using space satellites. In orbit thousands of miles above the earth, satellites will be able to relay not only telegraph and telephone messages but also television pictures, and they will be able to relay them not just between major countries but—as President Kennedy noted in a recent policy statement—to the farthest corner of the globe.

It would be a mistake to minimize the technical difficulties of creating a global communication network in space. As we shall see, they are formidable. Yet the attractions of such a network are so compelling that the incentives to get the job done are great. The short radio waves used in radiotelephony cross the oceans only by reflection from the ionosphere. Short-wave transmission is often of poor quality and sometimes it fails completely when the ionosphere is disturbed by solar storms. Submarine cables are greatly superior to short-wave radio for telephony, but they are only a little more effective in providing broad-band transmission capacity. The original 1956 cable between North America and Great Britain had 36 voice channels, now increased to 96 by a high-speed switching device called TASI (for Time Assignment Speech Interpolation) that fits the additional channels into the pauses that occur in normal conversations. A new cable, to be finished in 1963, will be able to carry 128 voice channels without the use of TASI, and about twice that number with TASI, but their combined band width is still far short of the 1,000 channels needed to carry a full television signal. In fact, the total number of voice channels now available—both radio and cable—between North America and overseas points throughout the world is now only about 550. In contrast the number of transcontinental telephone circuits is almost 2,300.

With 76 million telephones in North America and 58 million in the rest of the world, the demand for transoceanic circuits can be expected to grow rapidly, even without considering the extraordinary band-width needs of television. Submarine cables now connect the U.S. with Europe, Hawaii, Puerto Rico and Cuba. Cables are being laid between Puerto Rico and Antigua in the British West Indies and between Florida and Jamaica. The longest cable yet planned, extending some 3,900 miles from Hawaii to Japan, is scheduled for completion in 1964. In addition, the British Commonwealth is building a world-wide cable network, which will cost $250 million. The band-width limitations of these cables will be essentially the same as those of the cables now in service.

The cables of large capacity that carry television signals overland are special coaxial cables consisting of a copper wire supported by polyethylene spacers inside a copper tube about three-eighths of an inch in diameter. To preserve the quality of the signal it must be boosted by repeaters every four to eight miles. The submarine cable is also coaxial, but its watery environment and the necessity for a long, trouble-free life enforce certain design restrictions. Partly because power is limited to what can be supplied at the two land terminals and partly because reliability must be emphasized, the repeaters are spaced about 45 miles apart. As a result the capacity of the present submarine cable is only about one-fiftieth that of the land coaxial cables.

The other overland communication system with broad-band capacity is the microwave relay, in which radio beams with frequencies between 4,000 and 12,000 megacycles are transmitted between line-of-sight relay towers. Essentially it is this system that would be extended to provide signal links between ground stations and satellites and back to earth again.

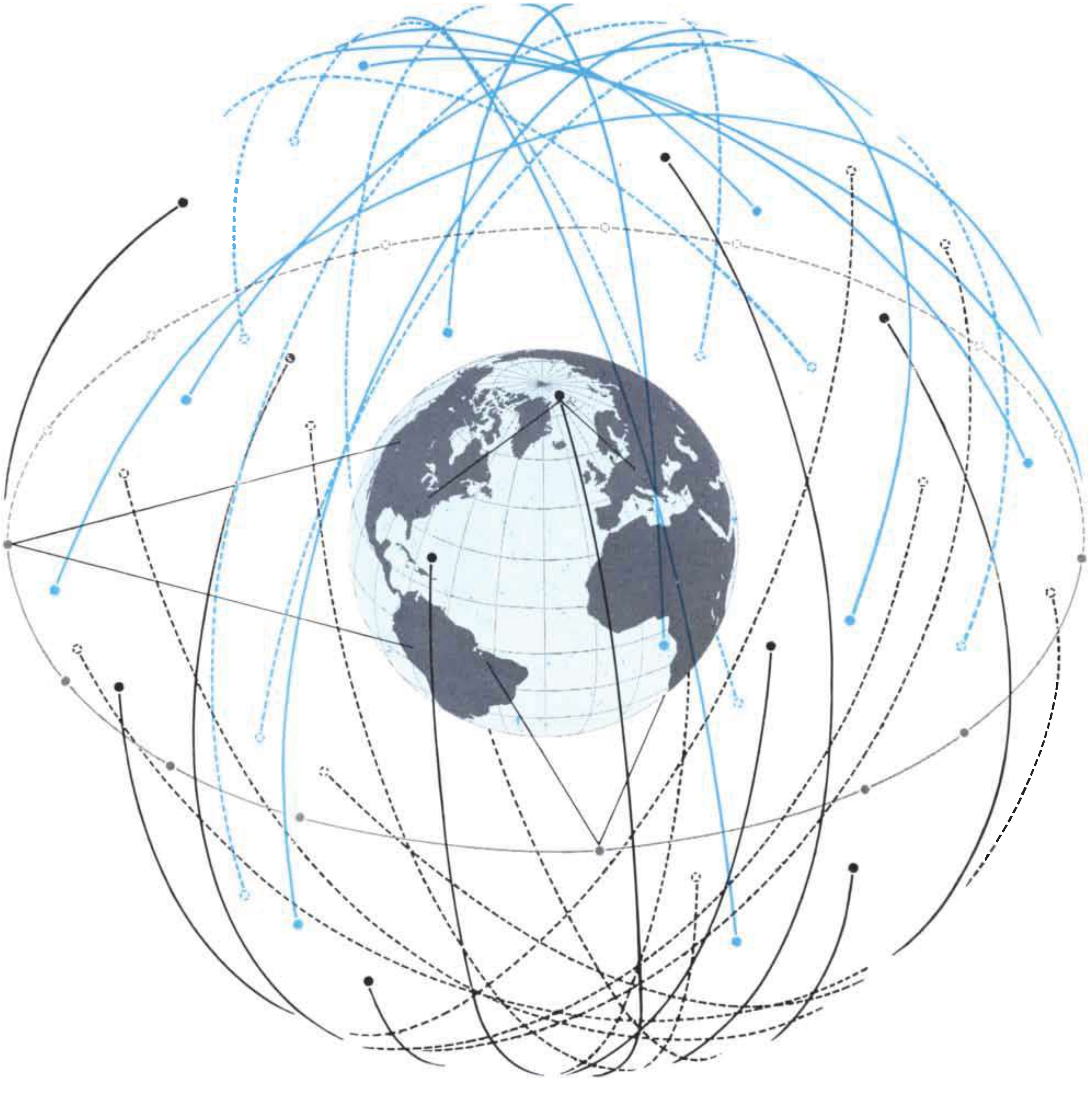
The Growth of an Idea

The idea of using satellites for communication is at least 16 years old. Arthur C. Clarke, a British science writer, proposed satellites for relaying and broadcasting in an article in *The Wireless World* in 1945. He pointed out that a satellite in an orbit 22,300 miles above the surface of the earth would complete one circuit of the earth in one sidereal day. If such a satellite were to move in the plane of the Equator and in the same direction as that of the rotation of the earth, it would hang stationary in the sky. If three such satellites were equally spaced in the same orbit, one or another of them would always be visible everywhere on the earth's surface except for a relatively small and virtually unpopulated region near each pole. Clarke proposed placing manned space stations in such an orbit and equipping them with radio broadcasting and relaying equipment.

When I first wrote about satellite communication in 1955, I proposed "passive" reflecting spheres such as the satellite *Echo I*, or oriented reflecting mirrors, as well as "active" satellites equipped with radio receivers and transmitters. I suggested that such satellites might be placed either in 22,300-mile-high "stationary" orbits or in lower orbits, where they would move more rapidly. In the latter case one would need to launch more than 30 satellites in order to assure that at least one of them would be visible at two ground terminal points almost all the time. The ground antennas would have to track such satellites as they moved across the sky.

In a paper delivered in London in 1960 at a meeting of the International Scientific Radio Union, Walter E. Morrow, Jr., of the Lincoln Laboratory of the Massachusetts Institute of Technology proposed a simpler sort of satellite system: a belt of fine wires half a radio wavelength long, circling the earth like the ring of Saturn. The ground-terminal antennas would point at a common portion of the belt, and the wires at that point would reflect a signal from the transmitter to the receiver. Different orbiting wires would of course serve as reflectors at different times. The position of the belt of wires could be stationary but not the positions of the wires forming it. A global system would require only two belts, one passing over the poles, the other circling the Equator [*see illustration on page 93*].

Both Clarke and I overlooked one important matter in connection with 22,300-mile-high stationary satellites: the finite speed of radio waves. The propagation time to and from a 22,300-



RANDOM-ORBIT SYSTEM, of the type proposed by American Telephone and Telegraph Company, could provide communication service 99.9 per cent of the time to any region on the earth's surface. The system would require 40 satellite repeaters (relay stations) in random polar orbits and 15 in equatorial orbits at an altitude of about 7,000 miles. With one-third more satellites the grade of service could be raised to 99.99 per cent; the average daily outage of 10 seconds could be predicted days in advance.

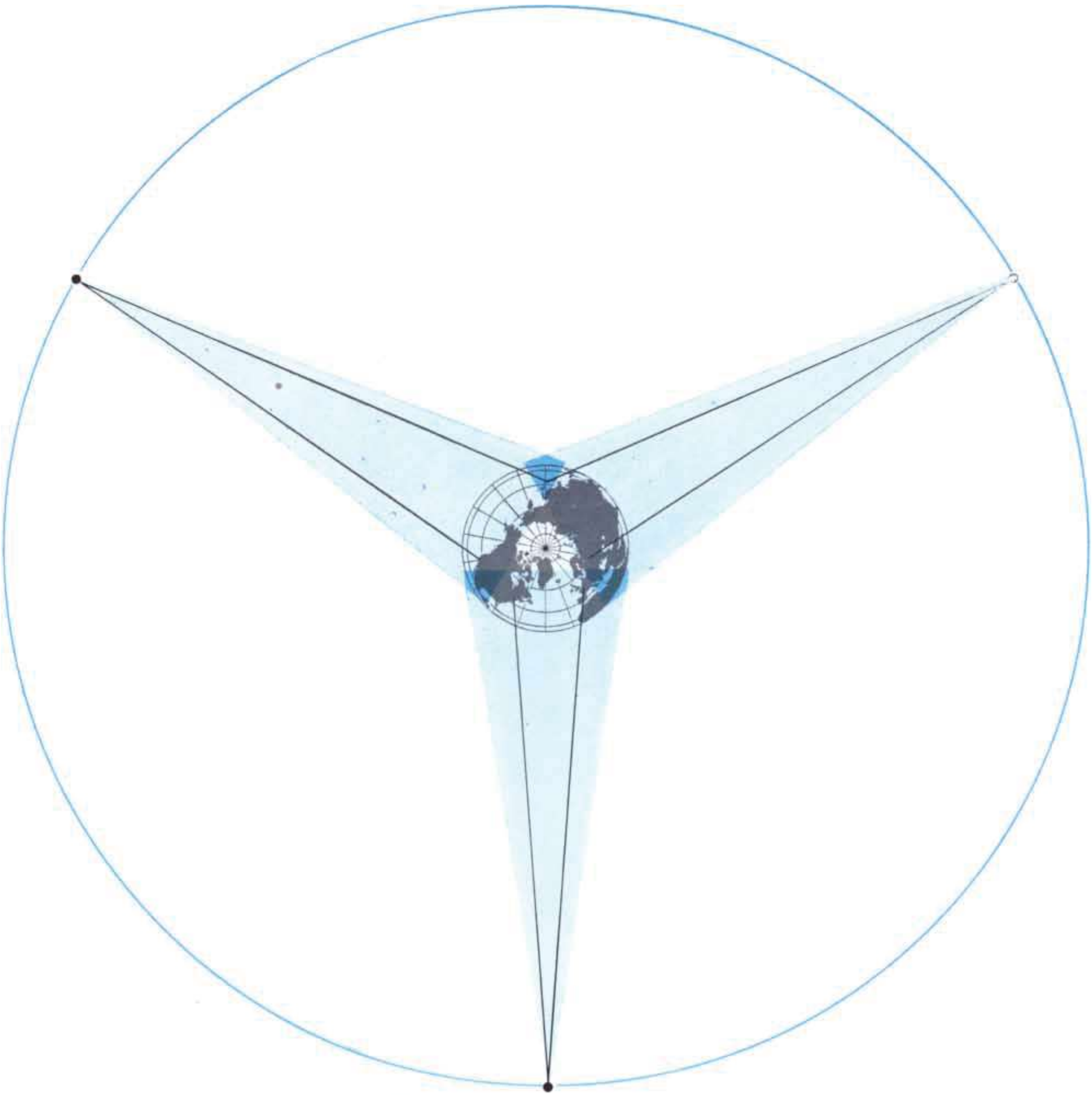
mile-high repeater is about a quarter of a second. Therefore a speaker cannot receive a reply to a remark for about half a second. Tests indicate that this delay may not interfere with a telephone conversation if a four-wire circuit is used; that is, if completely independent paths are provided from each telephone transmitter to each telephone receiver.

Actual telephone circuits, however, are always limited to two wire links, over which one both talks and listens. When a round-trip delay of half a second is introduced into such a circuit, an intolerable echo occurs. To get rid of the echo it is necessary to use an echo suppressor, which interrupts transmission at one end while the person at the other end is talking.

Echo suppressors do not seriously interfere with a conversation when the round-trip delay is less than a tenth of a second. Some preliminary experiments indicate that circuits with a delay of half a second and echo suppressors may be objectionable to a large fraction of users, and that conversation is sometimes brought to a halt when both users speak at once. Only further investigation will show how serious this really is.

The Satellites Themselves

It is a long step between proposing communication satellites and actually building them and making them work. A professional poet once told an amateur: "Sonnets are made of words, not of ideas." The realization of satellite



"STATIONARY"-ORBIT SYSTEM would require only three satellite repeaters (and perhaps a stand-by for each) equally spaced above the Equator at an altitude of 22,300 miles. Rotating eastward at the same apparent speed as the earth, they would seem to stand motionless in the sky. Since they would drift out of position periodically they would have to carry small rockets or gas jets that could be used to re-establish the proper orbit. A few extra satellites in polar orbits would be needed to serve the polar regions.

communication depends on the exploitation of two arts. One is the new, expensive and uncertain art of rocketry and space flight. To date only about half of U.S. satellite launchings have been successful. Satellite communication can come into being only through this art, and through the use of vehicles that have already been developed at great cost by the Government primarily for other purposes.

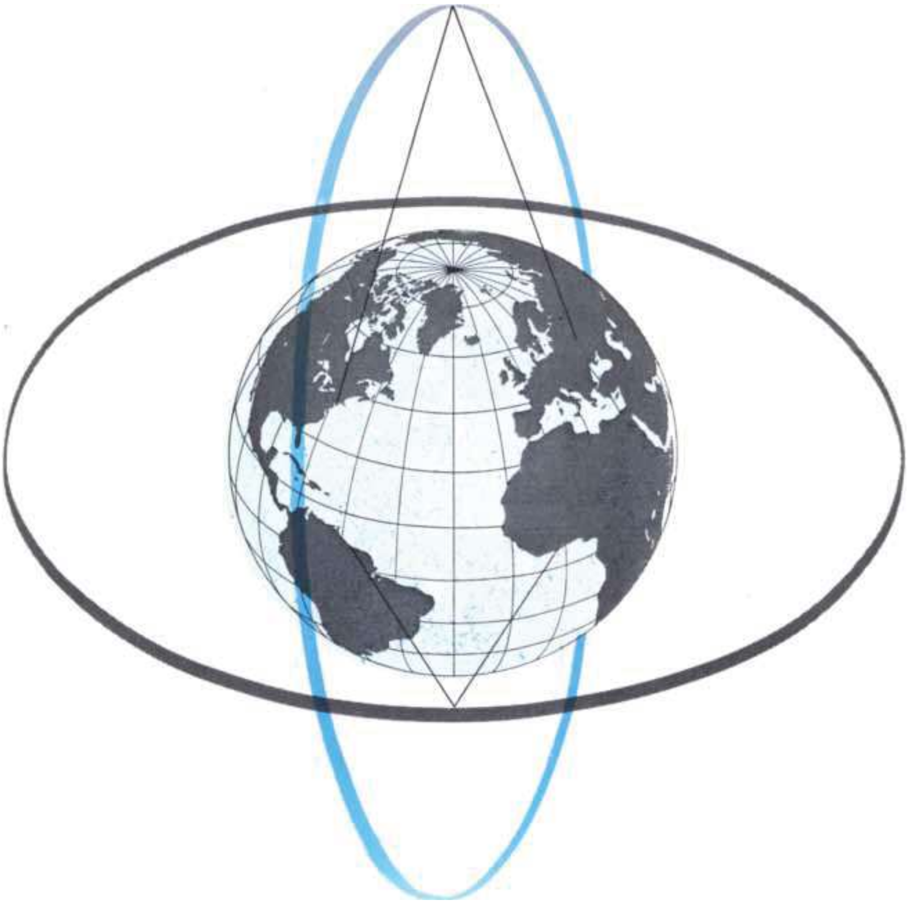
The other art is the mature one of electronics. So long as we stay on the ground, it can provide us with powerful transmitters, sensitive receivers, huge antennas, complex computers and tracking systems, and subtle methods of signal reception. The electronic space payload itself, however, is another matter. Repeated operational failures show us that it presents new problems.

I shall say nothing further concerning the problems of launching and guidance. Let us consider related problems that are very important to some types of satellite communication: maintaining the satellite in an appropriate orbit (called "station-keeping") and maintaining it in its appropriate orientation in space.

If a 22,300-mile-high satellite is to hang stationary in the sky, periodic readjustments in orbit will be necessary. These can be made by gas jets or other impulse-producing means under radio control from the ground. Because of the distances involved the satellite should be equipped with a directional antenna that will beam power only to the disk of the earth, and this too will require periodic adjustment. Small adjustments could be made by spinning small flywheels in the satellite, thereby causing the satellite itself to turn in the opposite direction. Larger changes could be made with gas jets. Beyond this, if solar cells are used for power, one might wish to orient the solar cells with respect to the sun. All such adjustments could be made either automatically, by devices aboard the satellite, or by commands given from the earth.

What is the state of the art of station-keeping and orientation? Nose cones of Atlas rockets have been successfully oriented for tens of minutes. Satellites of the *Discoverer* series have been oriented for several days. If communication satellites are to compare economically with cables, they must be oriented for at least two years.

Over this period of time gas valves may leak, bearings may freeze, some brief malfunction of orientation gear may set the satellite spinning. If orientation and station-keeping gear depend on commands from earth, can we really count on its responding to our commands and being unaffected by signals of other origin? We will be able to answer such questions only on the basis of experiments and experience.



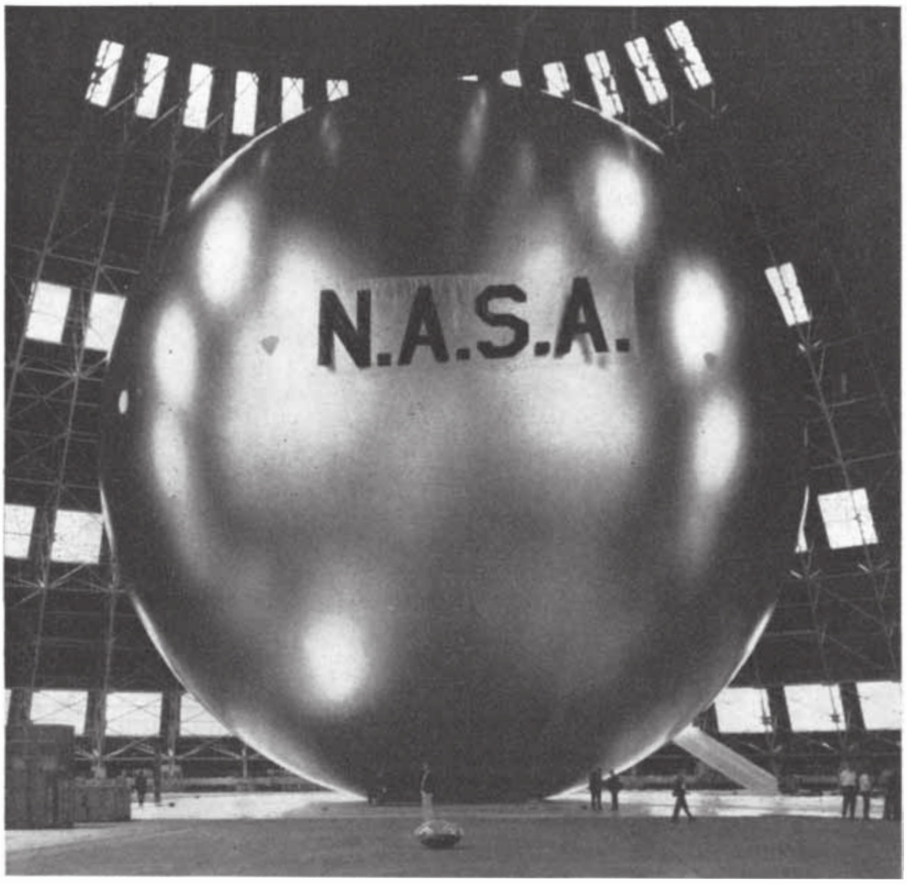
REFLECTING-WIRE SYSTEM, proposed by Lincoln Laboratory of the Massachusetts Institute of Technology, could provide global communications with only two tenuous rings, one polar and one equatorial, composed of millions of tiny wires about an inch long. The wires would circle the earth at an altitude of 3,000 to 4,000 miles. Ground stations in the northerly and southerly regions of the earth would communicate by bouncing signals off the wires traveling over the poles. Stations near the Equator would use the equatorial belt.

What one would like to find, of course, is some way to exploit natural forces to keep a satellite oriented automatically. One possibility is to use the earth's magnetic field, at least for medium-altitude satellites. At altitudes of a few thousand miles the earth's field is strong enough to serve as a reference and could even provide enough force to orient a space craft. At an altitude of 22,300 miles the field is not only small but also changes with time, since it depends in part on the flow of charged particles from the sun.

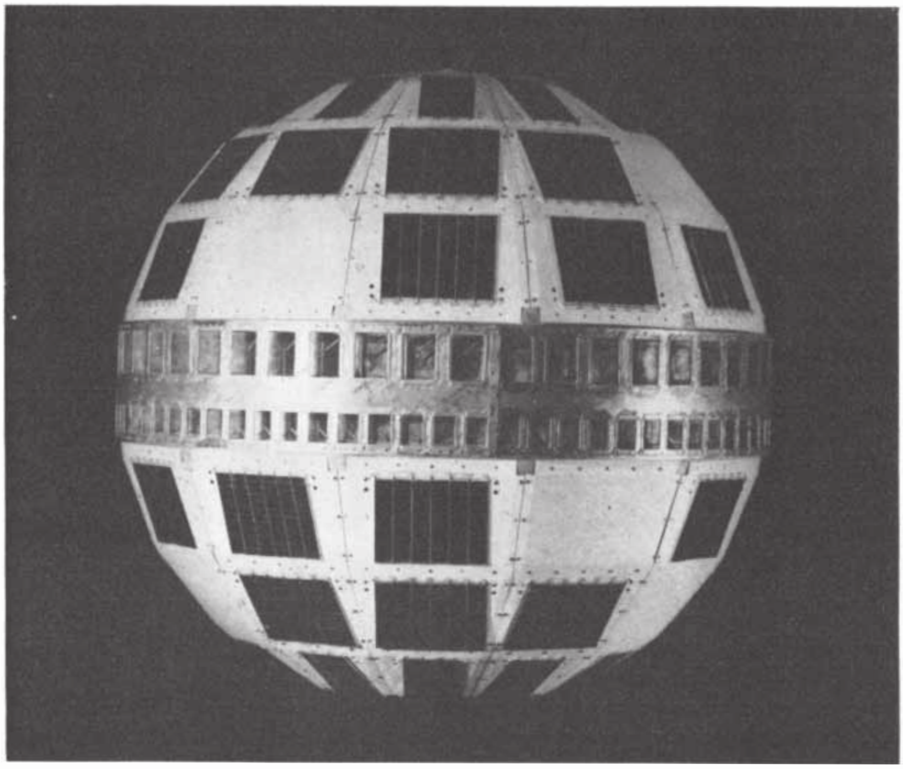
Still other natural forces might be exploited at low altitudes. For a given angular velocity centrifugal force increases with increasing radius of orbit, whereas the force due to gravity decreases with increasing radius. Imagine a satellite consisting of two equal weights tied together with a wire and aligned so that the wire points to the center of the earth. The centrifugal force will be greater on the outer weight, and the force of gravity will be greater on the inner weight. There will be a small tension in the wire. If the system is displaced, it will tend to return to its radial orientation.

But how small the force is! If the two weights are 100 pounds each and are 10 feet apart in an orbit 2,000 miles high, the tension in the connecting wire would be only about 20 milligrams. This is large, however, compared with some competing forces. Sunlight exerts a pressure of only about a tenth of a milligram for every square foot of shiny surface. The real problem is not lack of adequate force but the difficulty of damping out the slow oscillations that would keep the wired system from settling down in its desired orientation.

Simple spin orientation, used in the *Tiros* weather satellites, will keep the spin axis of a satellite pointed in one direction for a time. As a satellite travels through the earth's magnetic field, how-



ECHO II, 135 feet in diameter, is a larger and more rigid version of the first balloon satellite, *Echo I,* launched in August, 1960, and still in orbit. Made of plastic film about .0005 inch thick, vapor-coated with aluminum, *Echo I* became badly wrinkled within six months. For greater rigidity the plastic film of *Echo II* is laminated between two thin sheets of aluminum foil. It can be packed into a canister 41 inches in diameter for launching.



A.T.&T. EXPERIMENTAL SATELLITE, 34 inches in diameter, is being developed by Bell Telephone Laboratories. Antennas circle the satellite in two belts; solar cells are arrayed elsewhere on the surface. The National Aeronautics and Space Administration will launch the device next spring for a fee of about $6 million, to be paid by A.T.&T.

ever, small electric currents are generated within it and gradually retard its rate of spin. Such a satellite must be respun from time to time.

The Problem of the Van Allen Belt

Space poses problems beyond keeping satellites in place and oriented. One of the most serious is the effect of high-energy protons circulating in the inner Van Allen belt, which is most intense at an altitude of around 2,000 miles and which extends, with some diminution, to perhaps 5,000 miles. Electronic devices housed within the satellite will be reasonably well shielded from this proton radiation, but solar cells cannot easily be protected. Covering the solar cells with thin plates of sapphire, about a tenth of an inch thick, will shield them from the electrons of the outer Van Allen belt, which is most intense some 13,000 miles up, but it is not practical to use enough sapphire to protect them completely against the more energetic protons. Because of uncertainties in the extent, intensity and composition of radiation in the inner Van Allen belt, we are uncertain as to when the efficiency of a solar cell will fall to some preset design limit, say 5 per cent. The best present estimate is that in the center of the inner Van Allen belt solar cells will retain more than half of their original efficiency of 13 per cent for about 10 years.

Other problems are concerned with vibration and acceleration during launching, temperature control once in orbit (where heat can be dissipated only by radiation), leakage of pressurized containers and so on. In sum, the practicality of satellite communication depends on obtaining long service life in the novel environment of space.

Transmission and Reception

Let us now turn to another class of problems: those concerned with the transmission and reception of signals. Because it is costly to put weight in orbit, satellite transmitters must be kept low in power. The weight of electronic circuitry itself is negligible. The chief source of weight is the power supply: solar cells and storage batteries. (Nuclear power sources may eventually offer weight savings, but this remains to be shown.) In designing an economic satellite communication system, therefore, one must use the lowest power consonant with highly reliable service. This power is determined not only by the sensitivity of receivers but also by the strength of competing signals—that is, by noise.

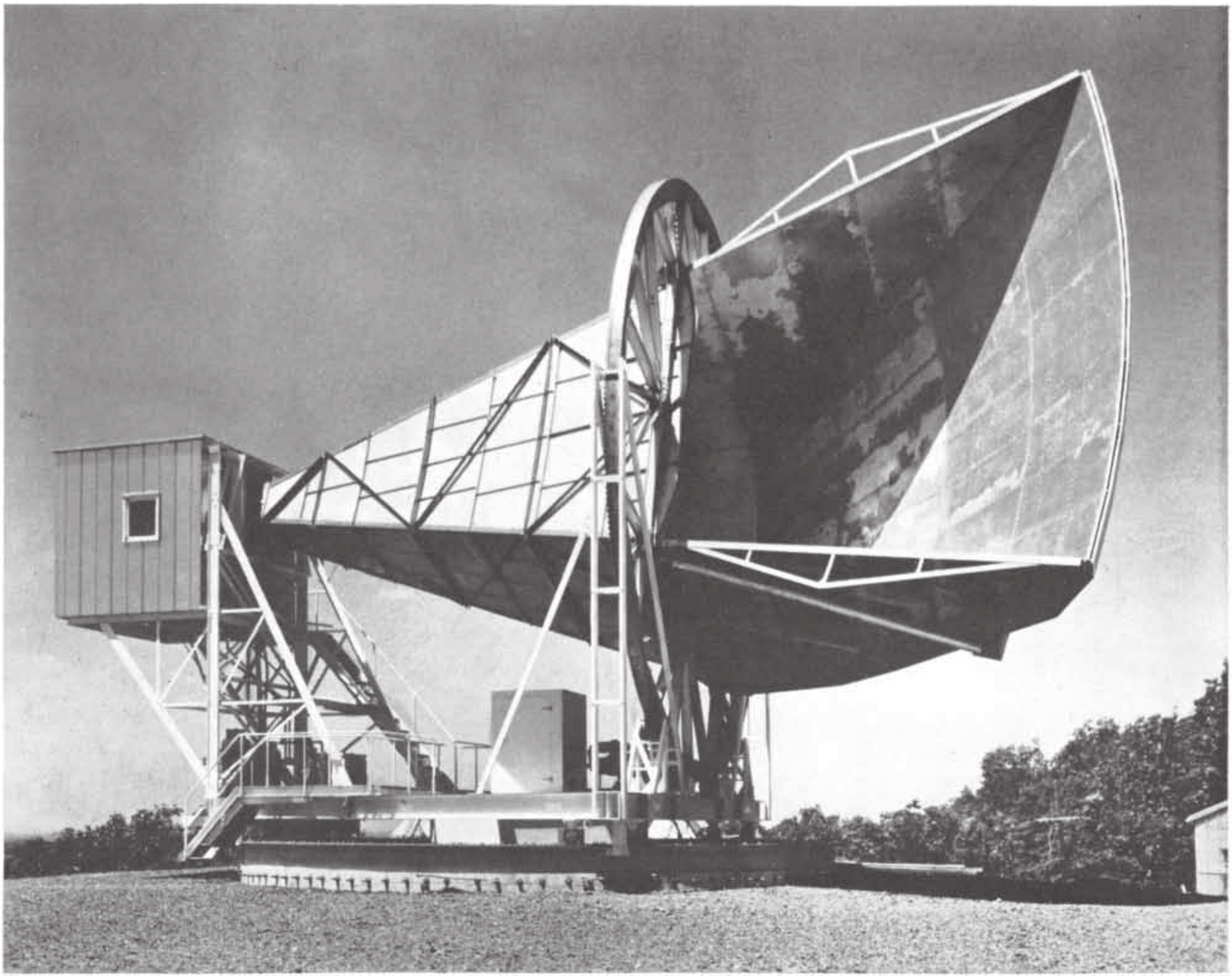
In evaluating the effects of noise we need some scale of measurement. A convenient scale is one based on the electromagnetic radiation emitted by hot objects. For example, the filament of an incandescent lamp glowing at a temperature of a few thousand degrees Kelvin (degrees centigrade above absolute zero) produces about the same amount of noise as that added to the signal by a good microwave receiver of 1950 design. Since then maser amplifiers have been developed with a noise level so low that it corresponds to a temperature of only about 10 degrees Kelvin. Hence it is now possible to detect signals that would have been hopelessly drowned in the noise produced by receivers of 10 years ago.

When we aim a ground antenna at a satellite sending signals from space, we must contend with background noise from a variety of sources. First there is the general cosmic noise discovered by Karl G. Jansky in 1932, which has led to the development of radio astronomy. This noise varies not only from point to point in the sky but also with frequency. Fortunately at microwave frequencies cosmic noise is not a serious problem.

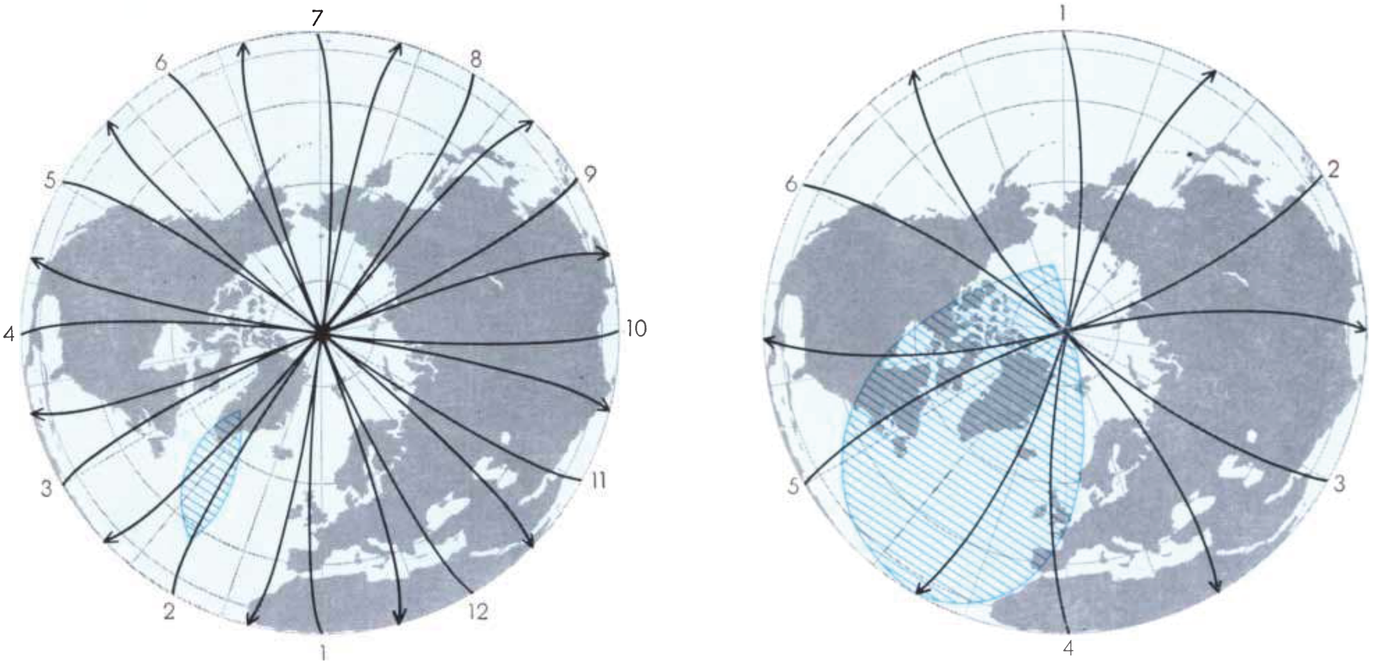
The sun, however, has a microwave noise temperature of about 6,000 degrees K. and the moon a noise temperature of about 70 degrees K. This means that one cannot receive signals from a satellite passing directly in front of the sun, and the signals will be somewhat noisy when the satellite is in front of the moon.

A more pervasive source of noise is the earth's atmosphere itself, which has a temperature of about 300 degrees K. Calculations and observations made by D. C. Hogg of the Bell Telephone Laboratories show that fortunately atmospheric noise is acceptably low for transmission frequencies lying between 1,000 and 10,000 megacycles, provided that receiving antennas are not pointed lower than 7 degrees above the horizon [*see bottom illustration on page 98*]. It would be undesirable in any case to aim antennas closer to the horizon, since they might then begin pulling in signals from ground microwave systems.

The solid earth also emits noise at a temperature of about 300 degrees K. A parabolic dish antenna pointed straight up receives, around the edge of the dish, noise corresponding to a temperature of about 50 degrees K. This residual



HORN-REFLECTOR ANTENNA, built by Bell Telephone Laboratories at Holmdel, N.J., is about 10 million times more sensitive to radio waves reaching it from in front than to radiation striking it from behind. Thus background noise contributed by thermal radiation from the earth's surface is minimized. The horn has been used to receive signals reflected from *Echo I*. The signals enter the open window in the horn and strike the aluminum reflecting surface at far right, whose curvature corresponds to an edge section cut from a parabolic dish. The reflector focuses the signals on a sensitive maser receiver housed at left. The antenna is about 50 feet long.



VISIBILITY RANGE OF SATELLITES is a major factor affecting the design of a space communication system. The areas shaded in color show where satellites traveling at various altitudes must pass to lie within radio “view” of both New York and Paris. The four altitudes depicted are, left to right: 1,040, 3,960, 6,450 and 12,550 miles, corresponding to orbital periods of 2, 4, 6 and 12

ground noise can be still further reduced by using a horn-reflector antenna [*see illustration on preceding page*]. This is an antenna whose reflecting surface is paraboloidal, corresponding to an edge section cut from a parabolic dish. The receiver is placed at the focus, and a metal horn extends from the focus to enclose the paraboloidal reflector. A window in one side of the horn permits the incoming radio waves to reach the reflector. Such an antenna is only about one ten-millionth as sensitive to radiation from behind as it is to radiation from in front. The horn reflector and maser receiver built to detect signals from the satellite *Echo I* achieved a noise level corresponding to a temperature of 24 degrees K. A noise temperature of 15 degrees K. seems attainable in the near future, and a value of less than 10 degrees K. seems possible.

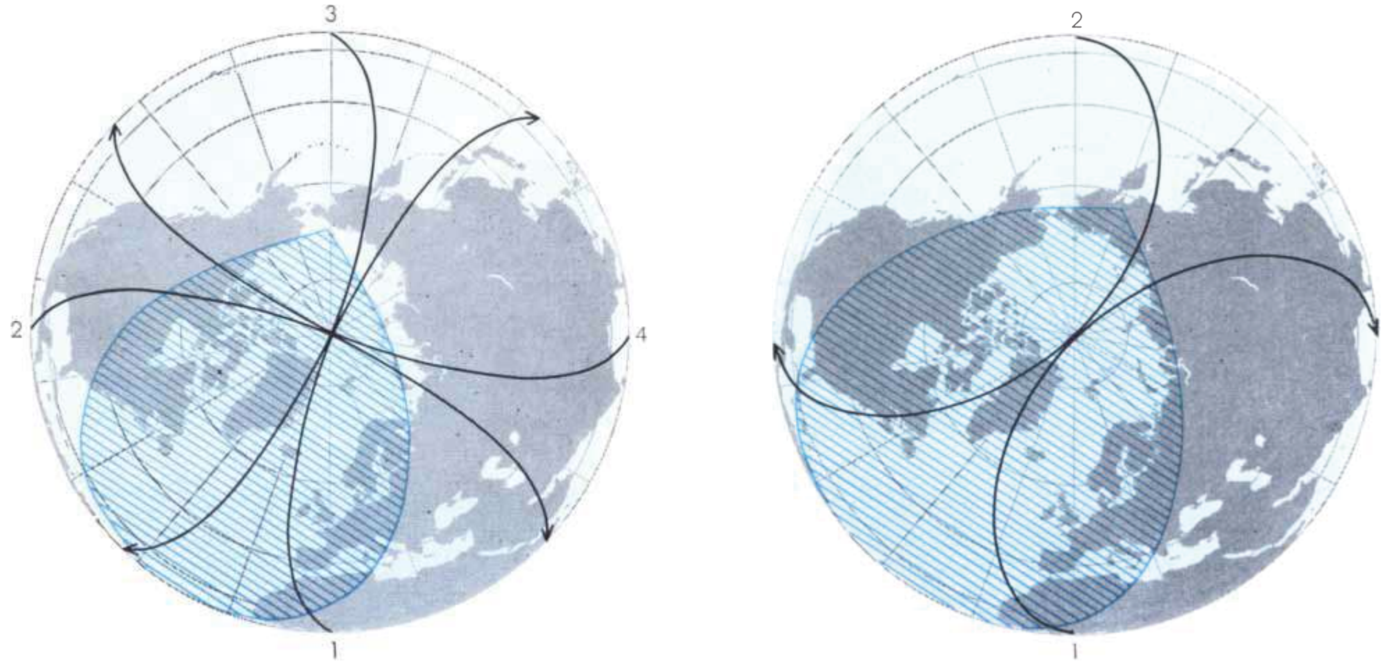
One other atmospheric source of noise remains to cause trouble: microwave noise arising from the heat of rain. Hogg has observed noise exceeding 100 degrees K. at 6,000 megacycles for a few minutes during a heavy storm, and noise as high as 70 degrees K. when no rain ever reached the ground. We cannot say how often rain noise might interrupt service in a satellite communication system. Interruptions could be minimized by using two receiving sites instead of one and spacing them far enough apart so that heavy rain would seldom be generating noise at each.

Having established the noise temperature of the sky, earth and atmosphere, the communication engineer next considers how noise is related to the band width of the signal he wishes to transmit and receive. The total noise power reaching a microwave receiver is proportional to the band width of the signal. Therefore the total noise power in a television channel will be about 1,000 times that in a telephone channel, because the television channel has about 1,000 times the band width of the telephone channel.

If this were all, one would merely need 1,000 times more power to transmit one television signal or 1,000 voice signals than to transmit one voice signal. Unhappily matters are much more complicated. A large number of people can talk simultaneously on one broad-band channel. One person talks only part of the time, and he talks loudly an even smaller fraction of the time. Thus the composite signal generated by 1,000 talkers has a peak power considerably less than 1,000 times that generated by one talker. It is clear that the amount of transmitter power required to provide a satisfactory received signal depends on the kind of signal to be transmitted as well as on the noise temperature and the band width.

The power required depends also on something else: the method of signaling, or modulation. Nearly everyone now knows that commercial radio employs two modulation methods: amplitude modulation (AM) and frequency modulation (FM). AM uses a narrow-band-width transmitter whose output is varied in amplitude in response to the original signal. In broad-band FM the transmitter frequency is varied, in response to the signal, over a frequency range that is many times the band width transmitted at any instant. If the frequency is varied up and down from the center frequency by 10 times the band width, the improvement in signal-to-noise ratio is about 100 times.

A rough, qualitative explanation of the improvement is as follows. Noise implies an uncertainty in measuring, at the receiving end, either the amplitude or frequency (or both) of the signal being transmitted at a given instant. In AM we are concerned only with the amplitude of the received signal, in FM only with its frequency. In AM we can vary the amplitude of the signal only from zero to twice its average value, and it is against this range of variation that we must measure the magnitude of the noise. To increase the signal-to-noise ratio in AM the sole recourse is to increase the average amplitude, which means raising the power of the transmitter. In FM, however, we can improve the signal-to-noise ratio by varying the frequency of the signal over an arbitrarily wide range. In sending a signal having a frequency of, say, 5,000 cycles per second we can, for example, vary the frequency of the transmitted signal back and forth over a range of 50,000 cycles per second, 100,000 cycles per second or even more than that. Since the uncertainty that noise introduces in our frequency measurement, at the receiver, remains more or less constant,



hours. The shaded areas exclude satellite positions closer to the horizon than 7.5 degrees, where signal reception would be impaired by background noise. In a two-hour orbit a satellite would spend at most only seven minutes within radio range of New York and Paris; in a 12-hour orbit it could be in range 4.5 hours. The calculations for these charts were made by Space Technology Laboratories.

it becomes a smaller and smaller fraction of the total frequency band over which the transmitted FM signal is swept.

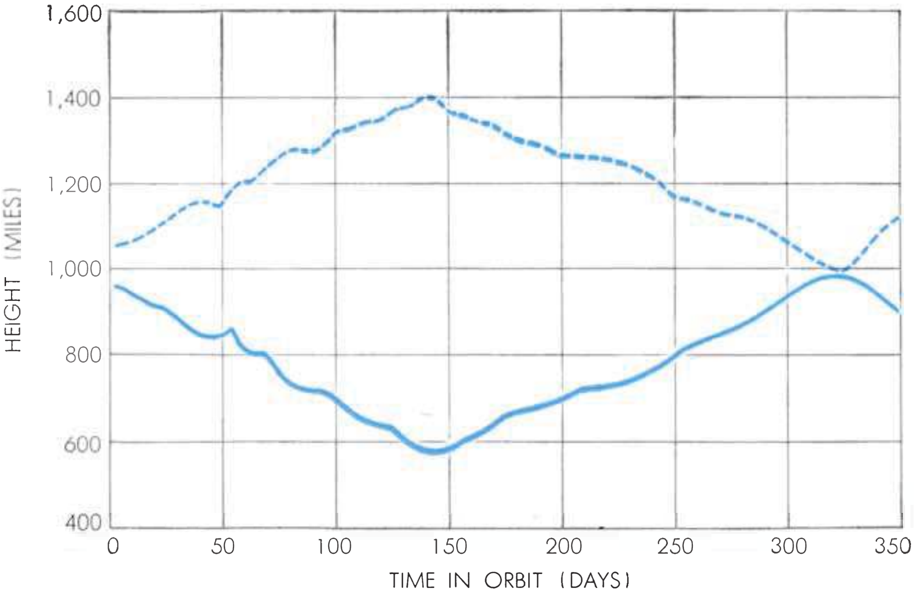
Ordinarily in receiving an FM signal a receiver must have a band width as wide as the total range of frequencies covered by the transmitted signal. Moreover, for the receiver to operate at all in the presence of noise the signal must be about 20 times more powerful than the noise. If the receiver band width is broadened to receive a wide-deviation FM signal, the receiver picks up noise across the entire band, and this minimum ratio of signal to noise may be hard to obtain.

Fortunately in 1939 J. G. Chaffee of the Bell Telephone Laboratories described a receiver for FM signals with a band width small compared with the range of frequencies over which the transmitter sweeps. In this receiver the output is "fed back" to alter the tuning of a comparatively narrow-band receiver, so that the receiver is always tuned to the received signal, regardless of how the signal frequency is swept back and forth. The use of Chaffee's FM-with-feedback receiver substantially reduces the transmitter power required in a satellite communication system. There are, of course, still other forms of broad-band modulation, including various pulse-modulation systems, that can provide a signal-to-noise advantage comparable to that gained with wide-deviation FM and an FM-with-feedback receiver.

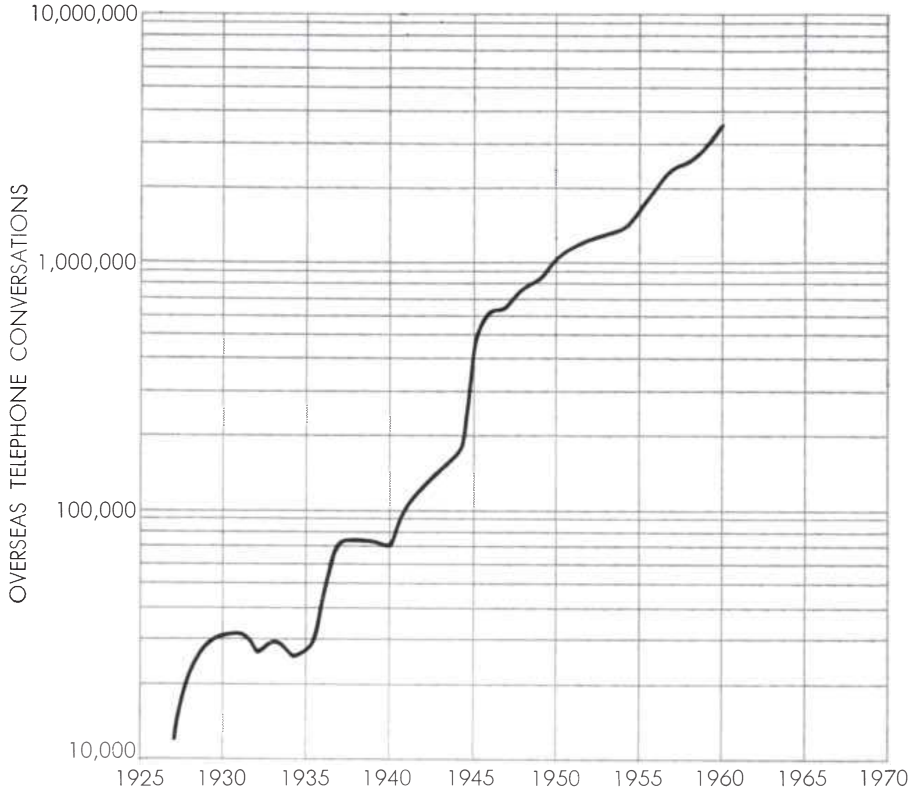
Now let us sum up the power requirements for a communication satellite, taking into account the various sources of noise, the capabilities of a maser receiver and the advantages of broad-band modulation. What power is required to transmit a television signal or between 600 and 1,000 telephone signals? We will assume a horn-reflector antenna with an aperture 60 feet square. For an unoriented satellite radiating equally in all directions at a height of from 2,000 to 3,000 miles, the required power is about two watts. Almost exactly the same power will serve for an oriented satellite at any greater altitude, up to and including one at 22,300 miles, if the satellite is equipped with a directional antenna that beams a signal just over the disk of the earth.

This is a particularly fortunate power level. In tests in progress, a type of microwave generator called a traveling-wave tube has continuously supplied somewhat more than five watts of power for more than four years and is still going strong. I believe that two-watt traveling-wave tubes could last for more than a decade in space.

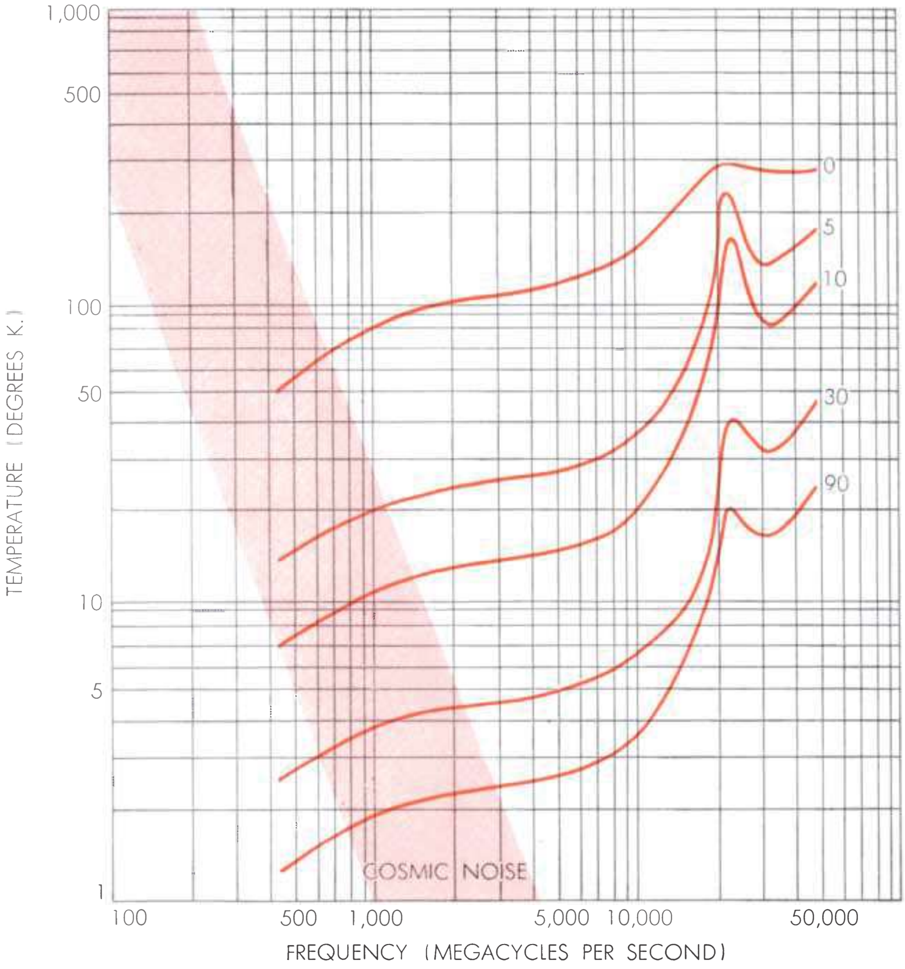
Moreover, a broad-band two-watt sig-



ALTITUDE OF *ECHO I* has varied curiously since its launching over a year ago. At first the slight pressure of sunlight raised the maximum altitude (apogee) while lowering the perigee. Later apogee and perigee came together; now the two are diverging again.



OVERSEAS TELEPHONE TRAFFIC has increased almost exponentially since the first radiotelephone circuit was opened between New York and London in 1927. In 1956 the first transatlantic telephone cable was placed in service with a capacity of 36 voice channels, since raised to 96. To all overseas points there are now some 550 radio and cable circuits.



NOISE INTERFERENCE with space communications is minimal at frequencies between 1,000 and 10,000 megacycles. Cosmic noise is radio noise from deep space. The five curves show the atmospheric noise reaching an antenna at various degrees of elevation.

nal will not interfere with conventional ground microwave receivers over which it may pass. Nor, because of the improved signal-to-noise ratio afforded by broad-band modulation, will the signal from a satellite in one part of the sky interfere with the simultaneous reception of a signal from a satellite in another part of the sky. The directivity of antennas will allow the simultaneous use of many satellites operating on the same frequency.

The Ground Stations

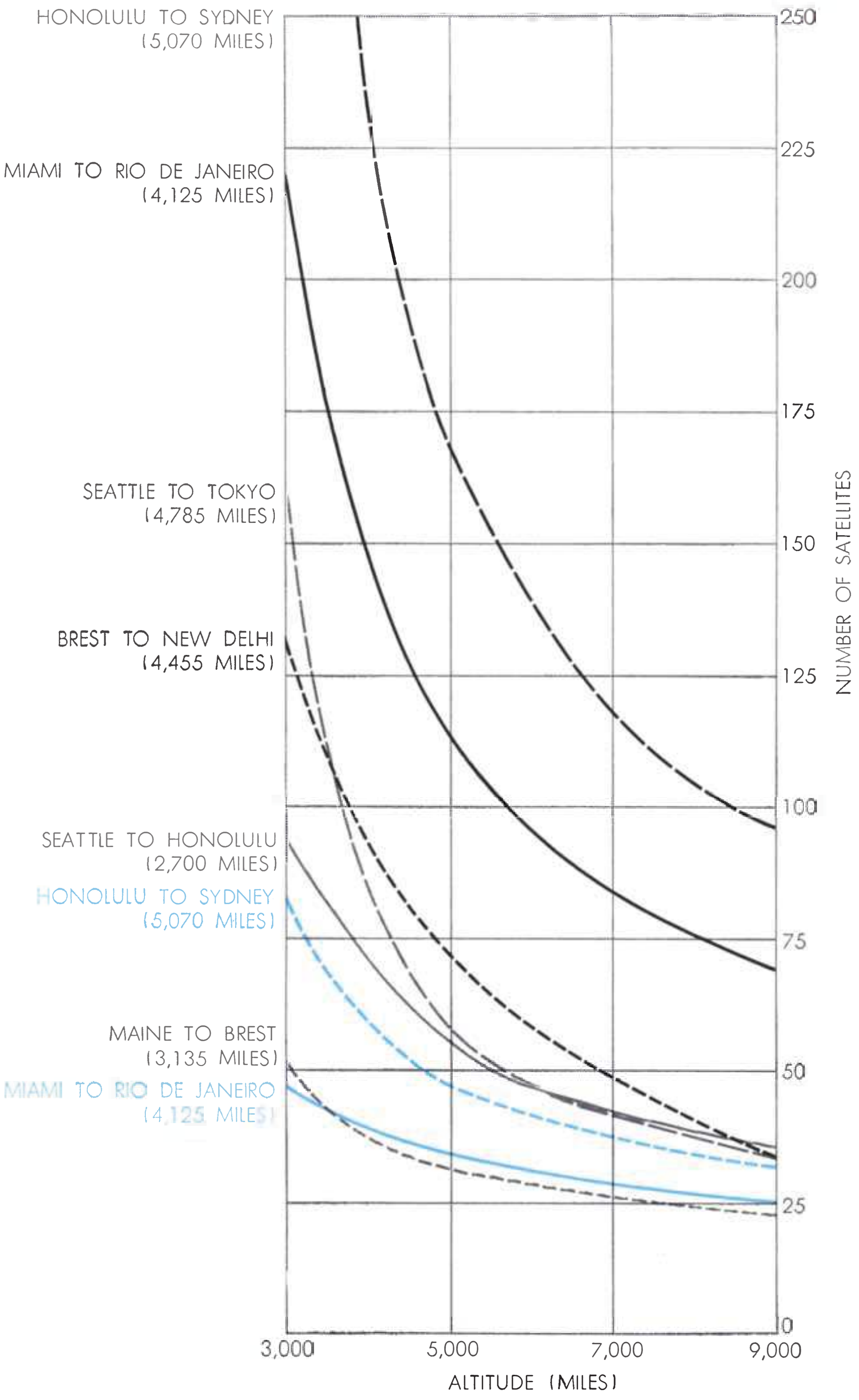
Compared with the problems already discussed, the problems associated with ground terminals are less serious. Some of them are well illustrated in Project Echo. Echo is a National Aeronautics and Space Administration satellite communication project in which Bell Laboratories has participated. A 100-foot, 130-pound aluminized plastic balloon was launched on August 12, 1960, in an orbit about 1,000 miles high, reaching an extreme latitude of 48 degrees. The orbit of *Echo I* has changed rapidly, chiefly because of the intermittent pressure of the sunlight and in part because of atmospheric drag [*see illustration at bottom of preceding page*].

The Echo balloon carries, for tracking purposes, two 108-megacycle transistorized transmitters powered by solar cells. (The transmitters are now dead.) For communication purposes the balloon was illuminated by signals from a number of ground stations. The principal exchange of signals took place between the Holmdel station of the Bell Telephone Laboratories in New Jersey and the Goldstone station in California operated by the Jet Propulsion Laboratory of the California Institute of Technology. Holmdel transmitted at 960.05 megacycles using a 10-kilowatt transmitter feeding into a dish antenna 60 feet in diameter. Goldstone illuminated the balloon at 2,390 megacycles with an 85-foot dish antenna and received Holmdel's reflected signals with the same antenna. Holmdel used a horn-reflector antenna to receive Goldstone's signals.

A rather elaborate system was devised for pointing the Holmdel and Goldstone antennas accurately at *Echo I*. Signals from the balloon were received by the Minitrack network of the National Aeronautics and Space Administration, and in addition the balloon was tracked by radar. Radar data and data from Minitrack stations were transmitted to the Goddard Space Flight Computation Center in Washington.

The center computed the satellite's orbit and also the data needed for pointing the antennas. The pointing data were transmitted to Holmdel and Goldstone by teletypewriter and received on punched tapes. At four-second intervals the tapes provided data for time, azimuth, elevation and rate of change for both asimuth and elevation. The tapes were fed into a digital-to-analogue converter, which then controlled the aiming of the antennas. The errors usually ran to about 10 minutes of arc, which corresponds to about one-third of the visual diameter of the moon. Optical and radar tracking were available to correct or replace the computed tracking.

Goldstone's 85-foot antenna and asso-



NUMBER OF SATELLITES required to provide service 99.9 per cent of the time between typical pairs of cities declines sharply as satellite altitude increases (*also see illustration at top of pages 96 and 97*). The black and gray curves are for satellites in random polar orbits. For connecting cities lying close to the Equator, or on opposite sides of it, satellites in equatorial orbit (*colored curves*) are much more effective than satellites in polar orbit.

ciated receiver, employing a parametric amplifier, had a noise temperature of about 300 degrees K., compared with 24 degrees K. for Holmdel's more sensitive maser receiver and horn-reflector combination. When the Echo balloon was in the most favorable part of its orbit, the signal received at Goldstone was about 24 decibels, or about 250 times, above the noise in a six-kilocycle band; the signal at Holmdel, about 34 decibels, or 2,500 times, above the noise. When the balloon was in the most unfavorable position for sender and receiver, the signal-to-noise ratios deteriorated by a factor of almost 10. If a narrow-band form of modulation (for example, AM) had been used, these lower signal-to-noise ratios would have been too low to provide a good telephone circuit. The signals were actually transmitted in broad-band FM and received by FM-with-feedback, and in general achieved the high quality expected. Two-way telephone conversations were conducted between Holmdel and Goldstone, and telephone pictures and "speedmail" were successfully transmitted. Clear signals reflected from Echo were also received in Europe.

In spite of the technical success of the Echo experiment, one must conclude that signal reflection from this passive type of satellite is only marginally practical as a means of communication. The balloon became increasingly wrinkled during its first six months in orbit, and as a result the reflected power began to fluctuate over a range of more than 10 to 1. Development of a rigid balloon might solve this problem, but there are other difficulties. To achieve a five-megacycle band width, which would be suitable for carrying 1,000 telephone circuits or one television channel, it would be necessary to use transmitters with 50 to 100 kilowatts of power and receiving antennas more than 100 feet in diameter.

Proposed Experiments

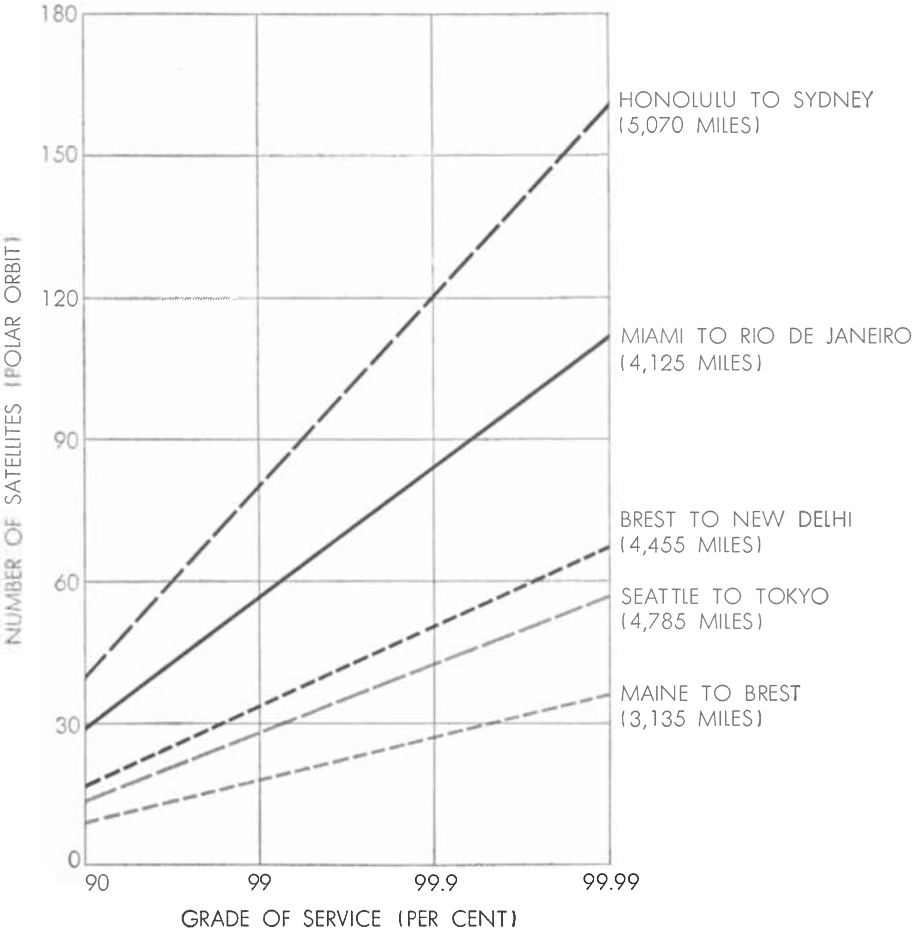
Until more experience has been gained with various types of satellite it is impossible to predict when a practical satellite communication system will arrive and what form it will take. It is proper, therefore, that vigorous experimentation be conducted.

The goal of the Army's Advent program is a system using 22,300-mile-high satellites with orientation control and station-keeping. Although this system may suit military requirements, the signal travel time to such distant satellites may prove unacceptable for commercial telephone service.

The Air Force plans an experimental launching of a belt of wires, which would provide a simple and effective communication system of limited band width. Astronomers have objected that the belt, being relatively fixed in space, might impair both optical and radio observations of the sky in a way that a moving satellite would not [see "Science and the Citizen" in this issue]. In any event, the initial belt will be placed low enough so that the wires will re-enter the atmosphere and be destroyed within a year or two. Experiments at higher altitudes could be conducted with wires that would disintegrate in a specified time.

As an alternative to high-altitude satellites, belts of wires and balloons, the American Telephone and Telegraph Company has proposed a system using between 50 and 120 simple active satellites in orbits about 7,000 miles high. With the large rockets now being developed, a dozen or more of these satellites could be placed in orbit in a single launching. In a relatively short time their orbits would assume random paths crossing—or nearly crossing—the poles. For efficient coverage between ground stations at low latitudes, a number of satellites should also be placed in orbit around the Equator. A system of 40 satellites in polar orbits and 15 in equatorial orbits would provide service 99.9 per cent of the time between any two points on earth. A.T.&T. has proposed that the system contain about 25 ground stations so placed as to provide global coverage. Bell Telephone Laboratories is building an experimental satellite to test the feasibility of such a system; NASA has agreed to launch it early next year for a fee of about $6 million, to be paid by A.T.&T.

The cost of a global satellite communication system will be large—on the order of $500 million—but no larger than the cost of undersea cables that could provide the same geographical coverage. (One cannot say the "same service," because undersea cables do not yet provide the band width needed for television.) Assuming that the experiments of the next few years are encouraging, there should be no lack of capital, domestic and foreign, to share the cost of a world-wide satellite communication system.



QUALITY OF SERVICE is proportional to the number of satellites used. The curves are for random polar orbits at an altitude of 7,000 miles. A service grade of 99.9 per cent means that communication will be interrupted .1 per cent of the time, or an average of 1.4 minutes per day, usually made up of several much briefer periods predictable well in advance.